Cavity dark matter searches using bosonic signal enhancement

Michael Romalis

Princeton University

Outline

- Experimental work:

  ⇒Search for Lorentz violation at the South Pole

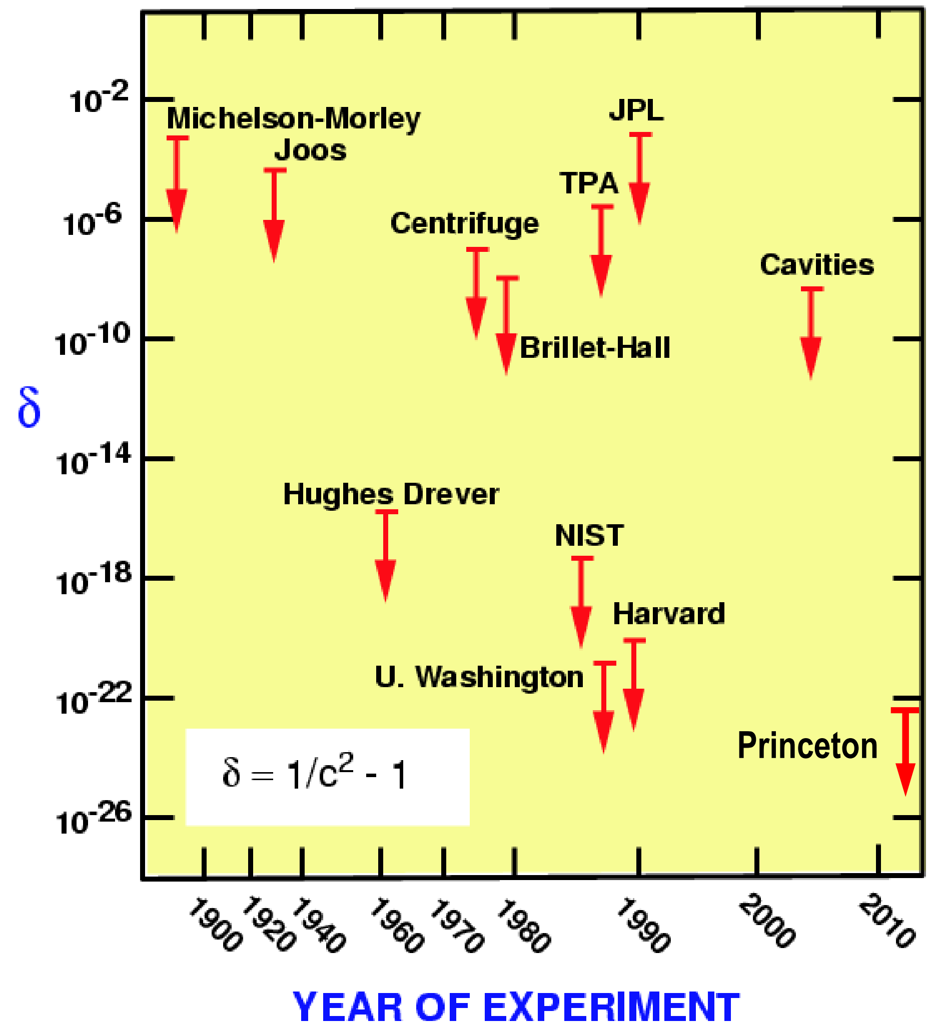
  ⇒Search for long-range axion-mediated spin-mass coupling at 20 cm scale

- Theoretical proposal:

  ⇒Cavity Axion/hidden photon searches –how to make them better with cavity QED.

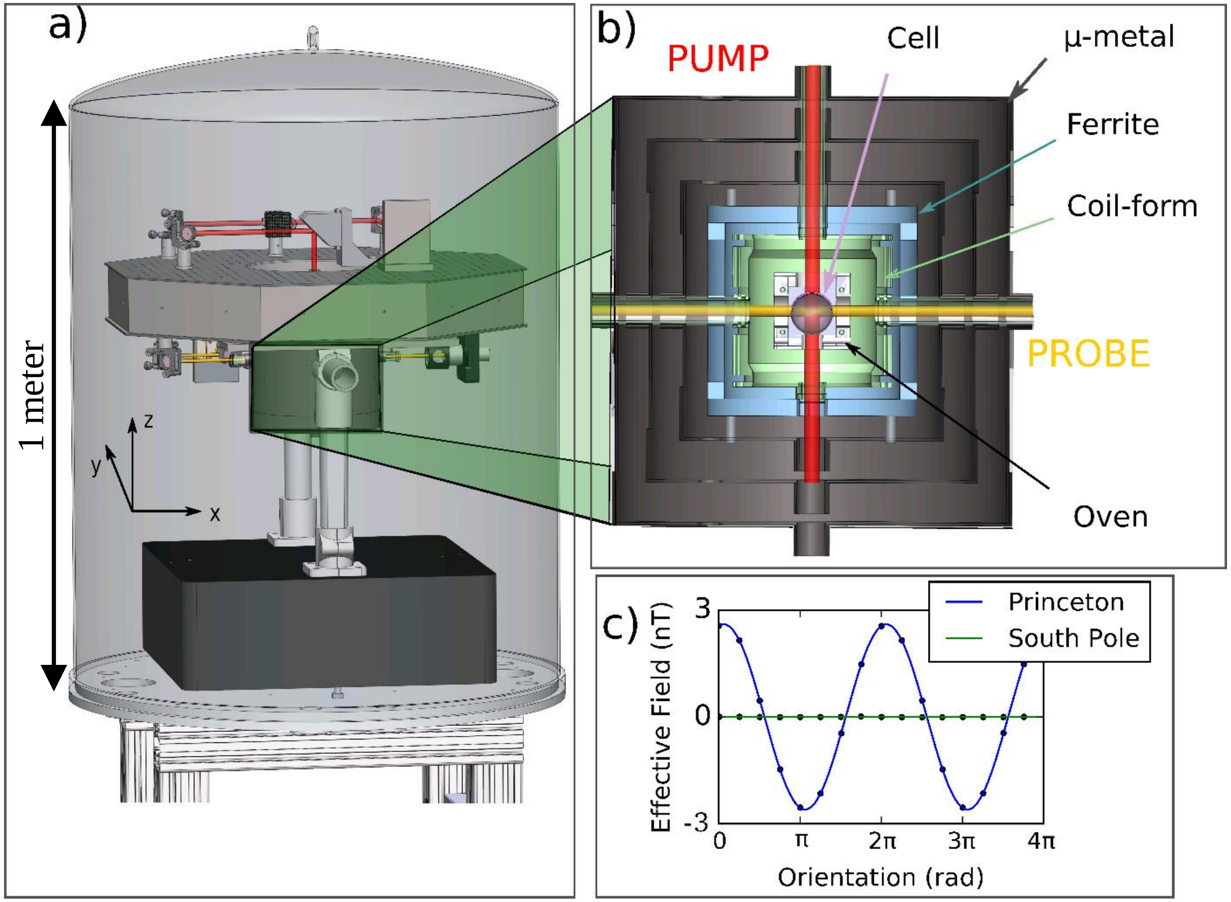
Local Lorentz Invariance

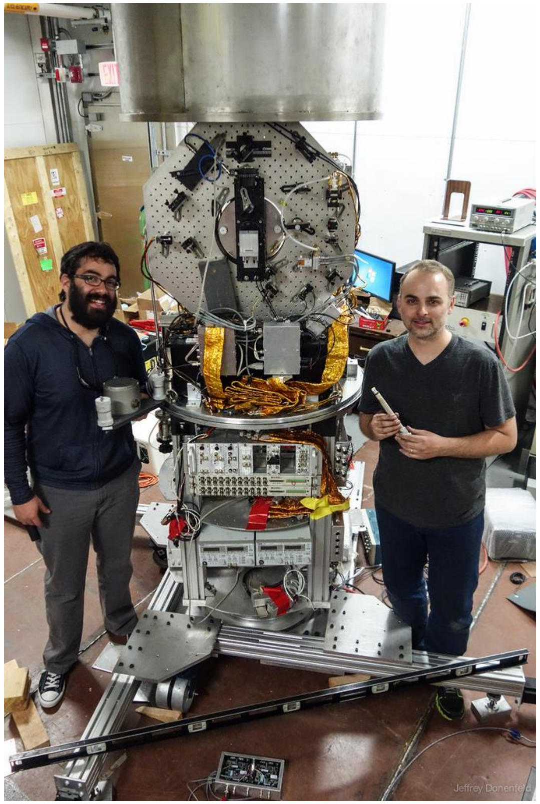
- Is the speed of light (photons) rotationally invariant in our moving frame?
  - ⇒ First established by Michelson-Morley experiment as a foundation of Special Relativity
- Is the speed of "light" as it enters into particle Lorentz transformation rotationally invariant in the moving frame?
  - ⇒ Best constrained by Hughes-Drever experiments due to finite kinetic energy of nucleons
- These two questions are actually closely related and we can answer both



From Clifford M. Will, *Living Rev. Relativity* **9**, (2006)

Lorentz violation test at South Pole



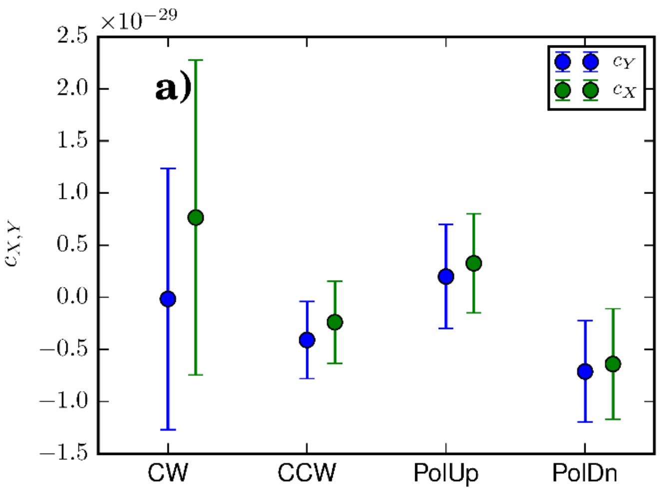


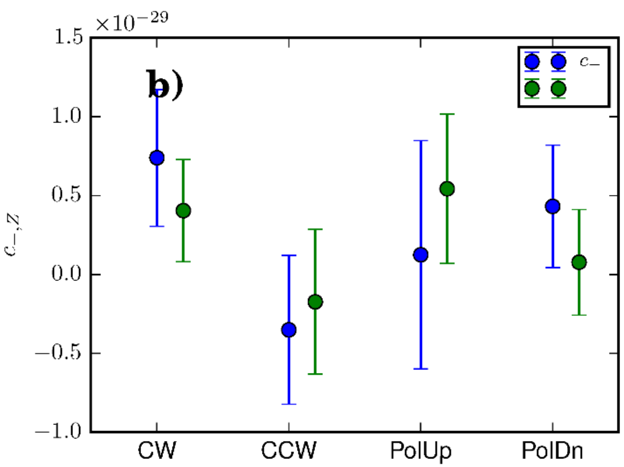
Reliable operation with minimal intervention:

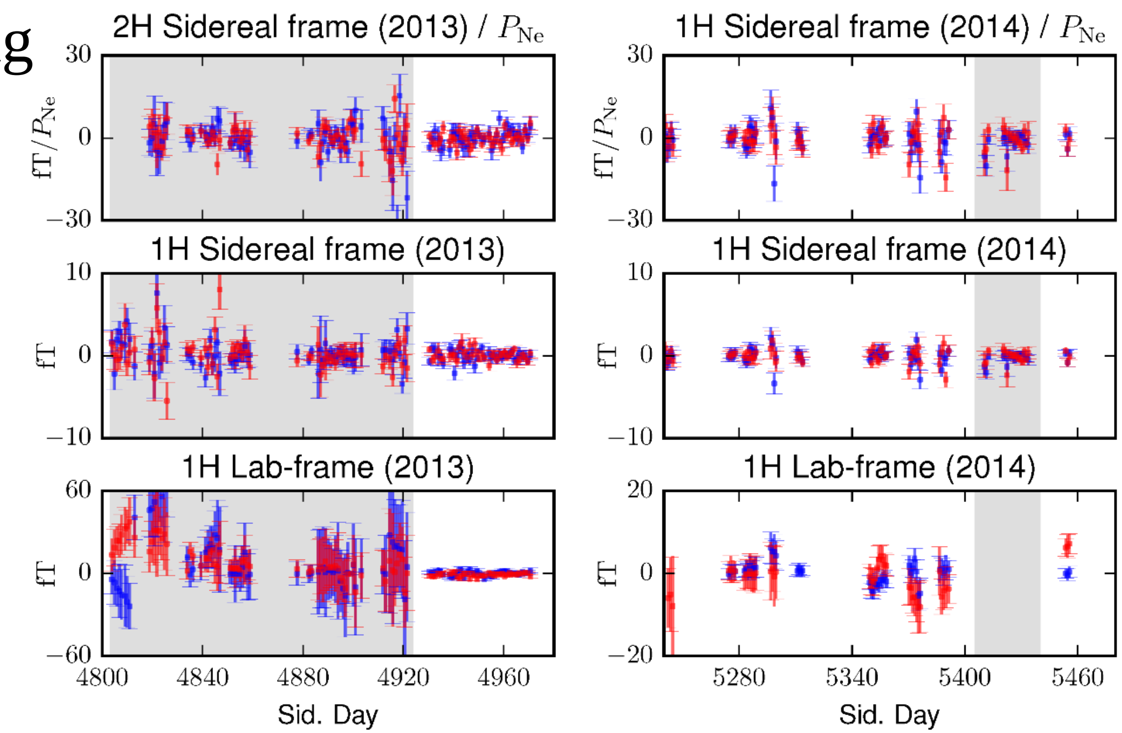
- Simple optical setup with DBR diode lasers
- Whole apparatus in vacuum at 1 Torr
- Automatic fine-tuning and calibration procedures
- Remote-controlled mirrors, lasers, tilt, etc

South Pole Results

- Two winters of data taking
- About 60% on factor





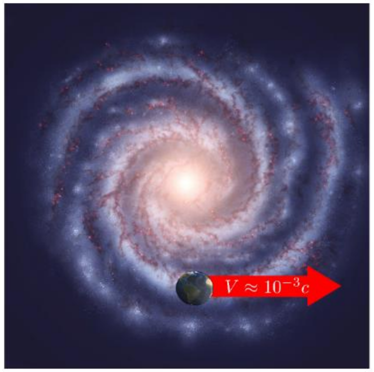


SME c_{ij}	Value	σ_{stat}	σ_{syst}	Improve
c_x	2.9×10^{-30}	3.9×10^{-30}	1.8×10^{-30}	10
c_y	3.1×10^{-30}	3.6×10^{-30}	1.8×10^{-30}	8
c_z	3.3×10^{-30}	3.4×10^{-30}	1.2×10^{-30}	3
c_-	2.9×10^{-30}	3.2×10^{-30}	1.2×10^{-30}	5

Slowly-modulated magnetic-like signals: very light axions

- Axion wind will generate slowly-varying pseudo magnetic field

$$H = g_{aNN} m_a a_0 \cos(m_a t) v \cdot \sigma$$



⇒v = 232 km/sec at 42° to Earth's axis.

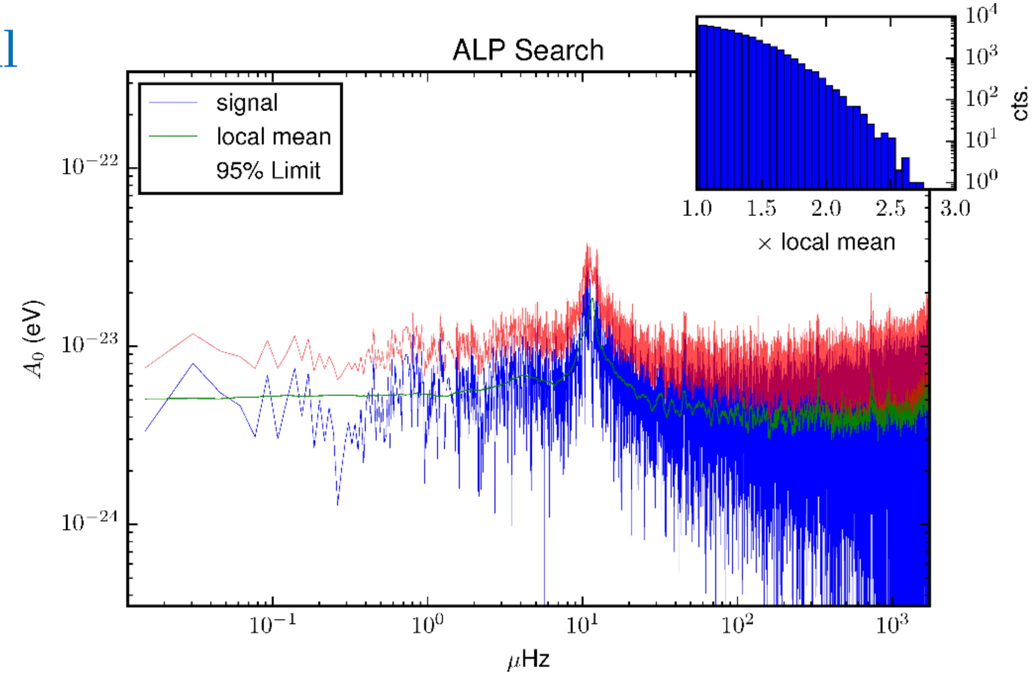
⇒Limit on energy shift ~10^{-23} eV

⇒Corresponds to $g_{aNN} = 5\times10^{-9}$ GeV^{-1}

⇒Limit obtained so far is slightly worse than SN1987A

⇒Much better than direct experimental limits from spin-dependent forces

⇒Extends to 10^{-22} eV, where there is some astrophysical evidence for fuzzy dark matter, possible string theory motivation



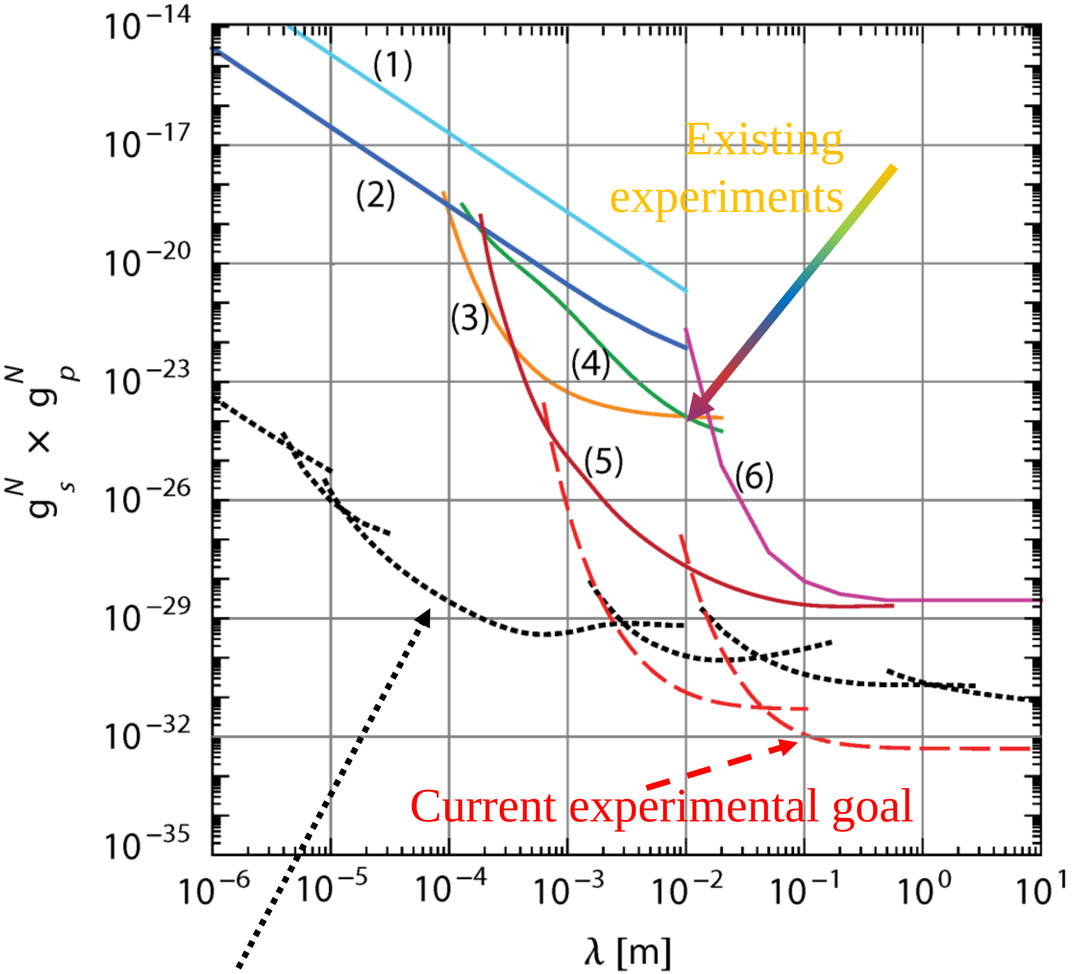
P.V. Vorobev, A.I. Kakhidze, I.V. Kolokolov
Phys. Atom. Nucl. **58**, 959 (1995), arXiv:astro-ph/9501042

P.W. Graham, S. Rajendran
Phys. Rev. D **88**, 035023 (2013)

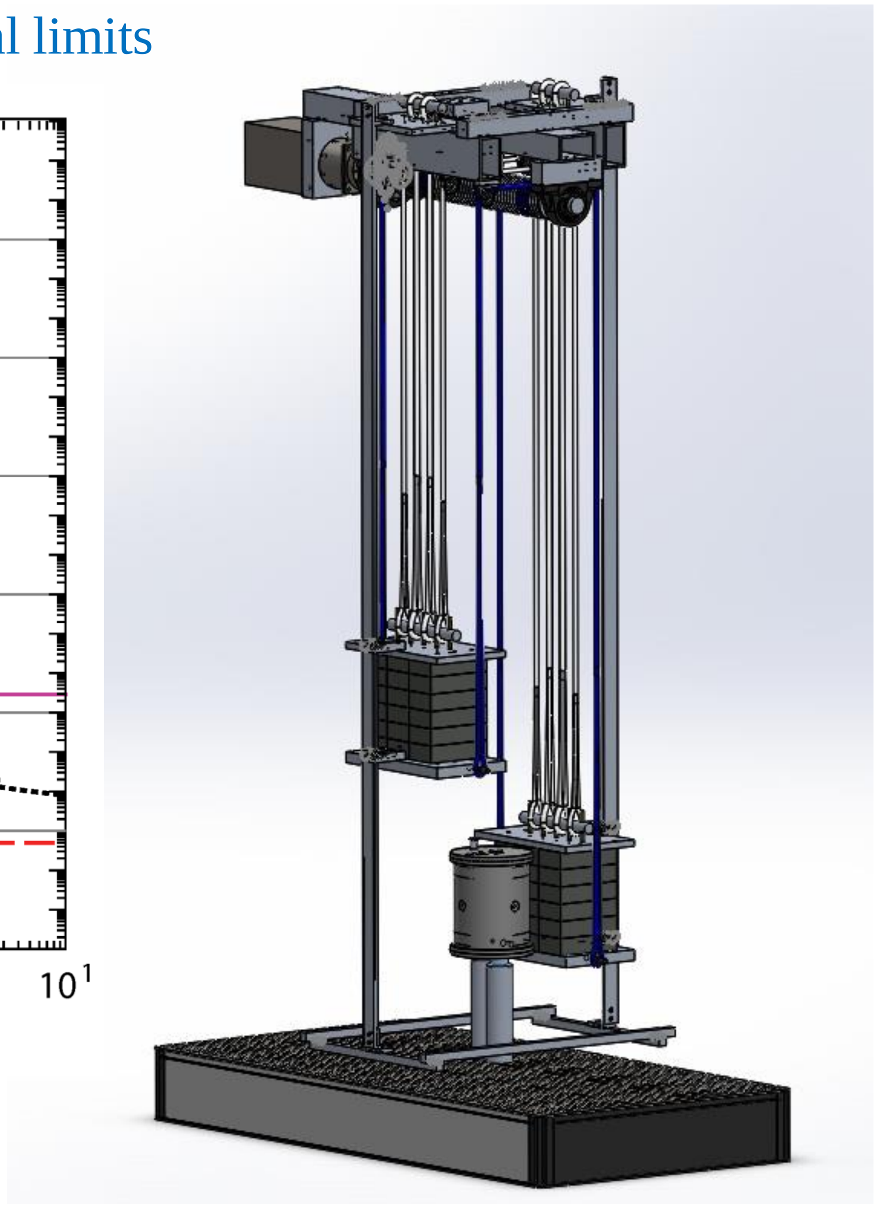
L. Hui, J. P. Ostriker, S.Tremaine, E. Witten, arXiv:1610.08297

Spin-mass searches with co-magnetometer

- Will be more sensitive than astrophysical limits

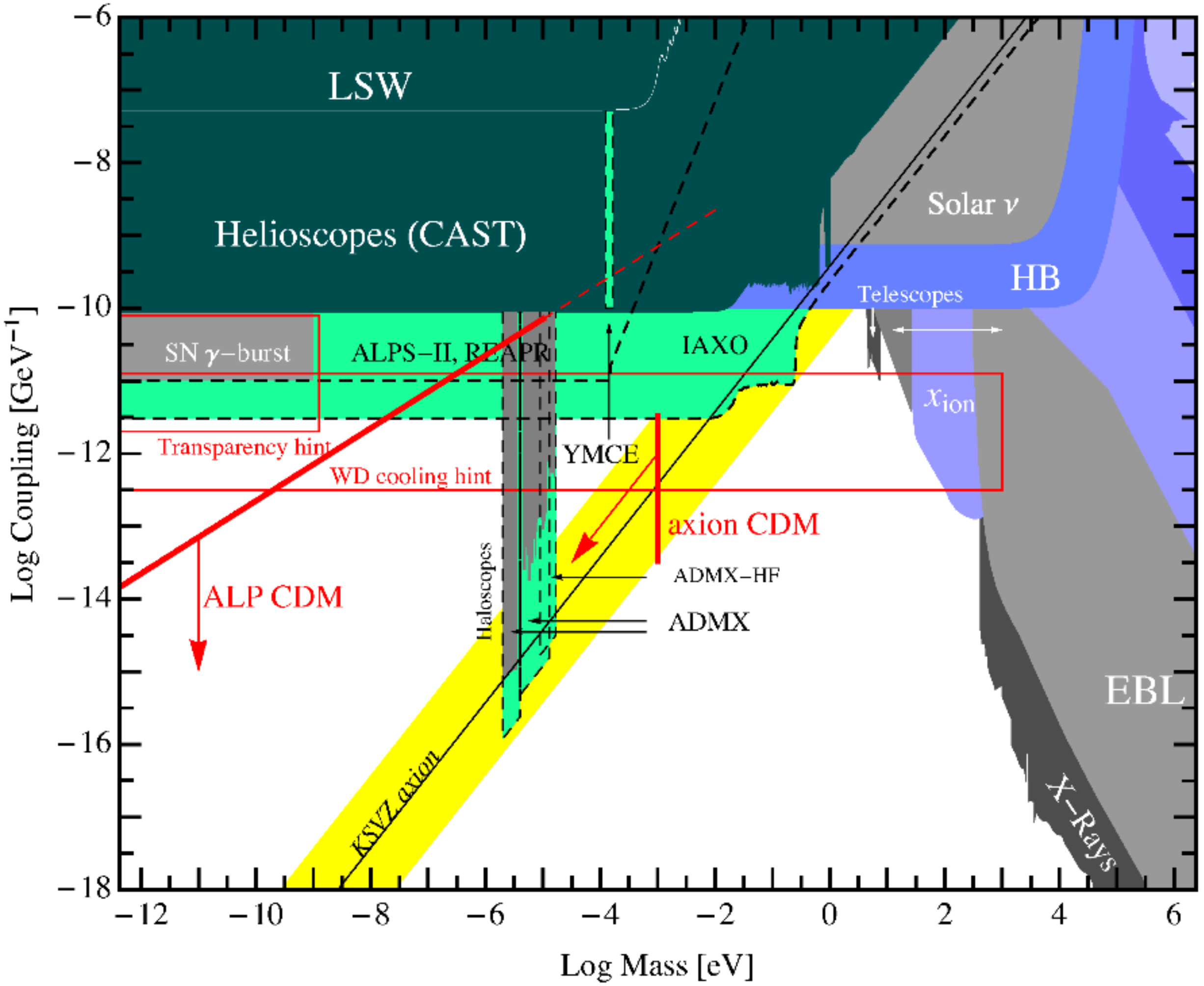


Astrophysical × gravitational limits from G. Raffelt
Phys. Rev. D **86**, 015001 (2012)



Cavity axion searches

- Sikivie's cavity haloscope is the only experimental approach that has been able to reach the QCD axion window.
- Can we improve on this basic approach?



Conversion rate of axions to photons

$$P_a = 3.4\times10^{-23}W\left(\frac{V}{100L}\right)\left(\frac{B}{8T}\right)^2\left(\frac{C}{0.5}\right)\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{0.3GeV/cm^3}\right)\left(\frac{m_a}{1\,GHz}\right)\left(\frac{\min(Q_L,Q_a)}{10^5}\right)$$

- Conversion rate 50 a/sec or 0.003 axions in cavity at any time
- At 100 mK physical temperature ~ 2 thermal photons present in cavity
- At higher frequency coupling goes up but volume goes down as λ_a^3
  $\Rightarrow$ Need multiple cavities in parallel or new geometries.
- For higher frequencies can suppress thermal photons: 5 GHz = 240 mK
- Use a single microwave photon counter or use squeezed states (S. K. Lamoreaux, *et al*, PRD **88**, 035020 (2013))
- An experiment called CARRACK: "Cosmic Axion Research with Rydberg Atoms in a Cavity at Kyoto" already used Rydberg atoms as photon microwave detectors (hep-ph/0101200)
- Increase *Q* of cavity, but doesn't seem to help if $Q_c > Q_a = 10^6$
- Can one benefit from $Q_c \gg Q_a$?

Bosonic conversion enhancement

- Cavity with a finite initial number of photons exposed to axion field:
  - ⇒Doesn't help, axions as likely to be emitted as absorbed

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

PACS numbers: 14.80.Gt, 11.30.Er, 95.30.Cq

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Finally, let us take note of the interest of trying to devise an experiment which exploits the very high quantum degeneracy of the axions in the halo of our galaxy. In particular, emission of axions with energies between m_a and $m_a[1+O(10^{-6})]$ is enormously stimulated {the rate is multiplied by a factor $10^{25}[v/(10^{12}\text{ GeV})]^4$}, and hence may become measurable. It is necessary, however, that the emitter does not equally well absorb axions; otherwise, stimulated emission and stimulated absorption will cancel each other, as is the case with a cavity or with any other *harmonic* oscillator coupled to the axion field.

Bosonic conversion enhancement

- Cavity with a finite initial number of photons exposed to axion field:

  ⇒Doesn't help, axions as likely to be emitted as absorbed

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

PHYSICAL REVIEW D VOLUME 42, NUMBER 5 1 SEPTEMBER 1990

Nuclear dipole radiation from $\bar{\theta}$ oscillations

Jooyoo Hong and Jihn E. Kim
Department of Physics, Seoul National University, Seoul 151-742, Korea

P. Sikivie
Department of Physics, University of Florida, Gainesville, Florida 32611

(Received 19 March 1990)

The oscillations of the vacuum angle $\bar{\theta}$ due to a cosmological axion field will induce oscillating electric dipoles onto nuclei. We discuss the observability of the resulting nuclear dipole radiation.

emitter does not equally well absorb axions; otherwise, stimulated emission and stimulated absorption will cancel each other, as is the case with a cavity or with any other *harmonic* oscillator coupled to the axion field.

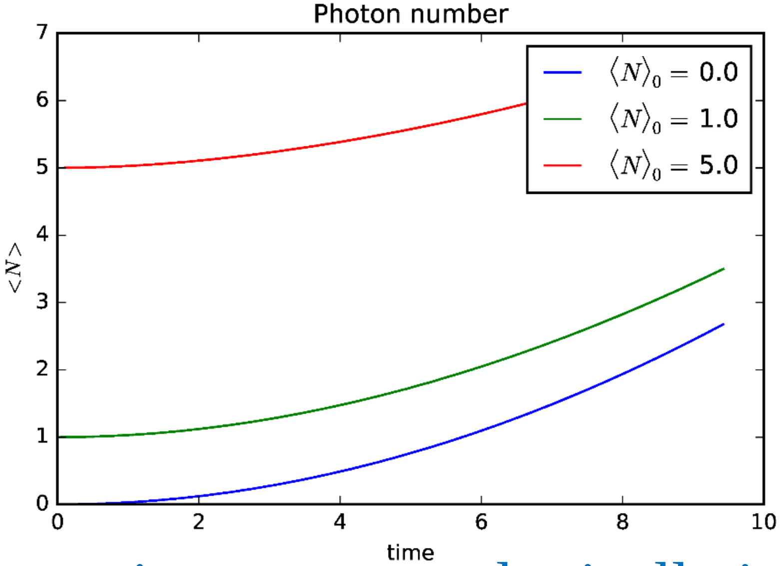
Bosonic conversion enhancement

- Model cavity-axion interactions using cQED

$\Rightarrow$ The axion field A is assumed to be classical

$$H = \hbar\omega_c \hat{a}^\dagger \hat{a} + gA(\hat{a} + \hat{a}^\dagger)$$

$\Rightarrow$ Indeed, the rate of axion-photon conversion does not depend on initial number of photons



- The number of photons created in the cavity grows quadratically in time until the time scale of the axion or of the cavity coherence, which ever comes first.

$\Rightarrow$ Hence improving Q_c of the cavity above Q_a does not help.

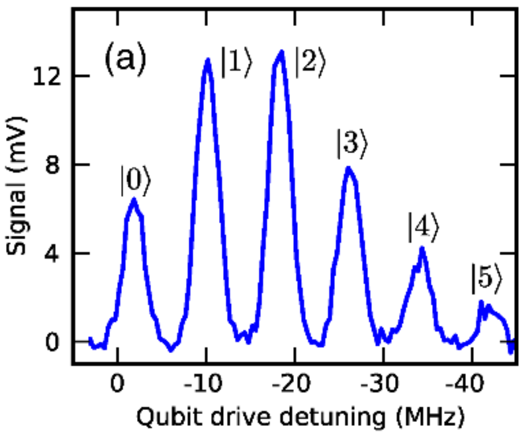
Aharmonic cavity

- Make cavity levels un-equally spaced, so only one pair is tuned to the axion frequency:

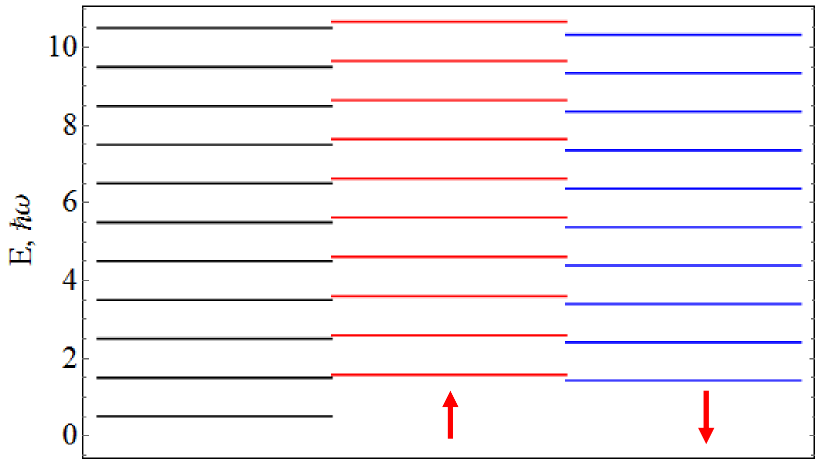
⇒Jaynes–Cummings coupling of a two-level spin to cavity

$$H = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_a \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}\left(\hat{a}\hat{\sigma}_+ + \hat{a}^\dagger\hat{\sigma}_-\right) + gA(\hat{a}^\dagger + \hat{a})$$

$$E_{n\pm} = \hbar\omega_c\left(n + \frac{1}{2}\right) \pm \frac{\hbar\sqrt{\Omega^2(n+1) + (\omega_c - \omega_a)^2}}{2}$$

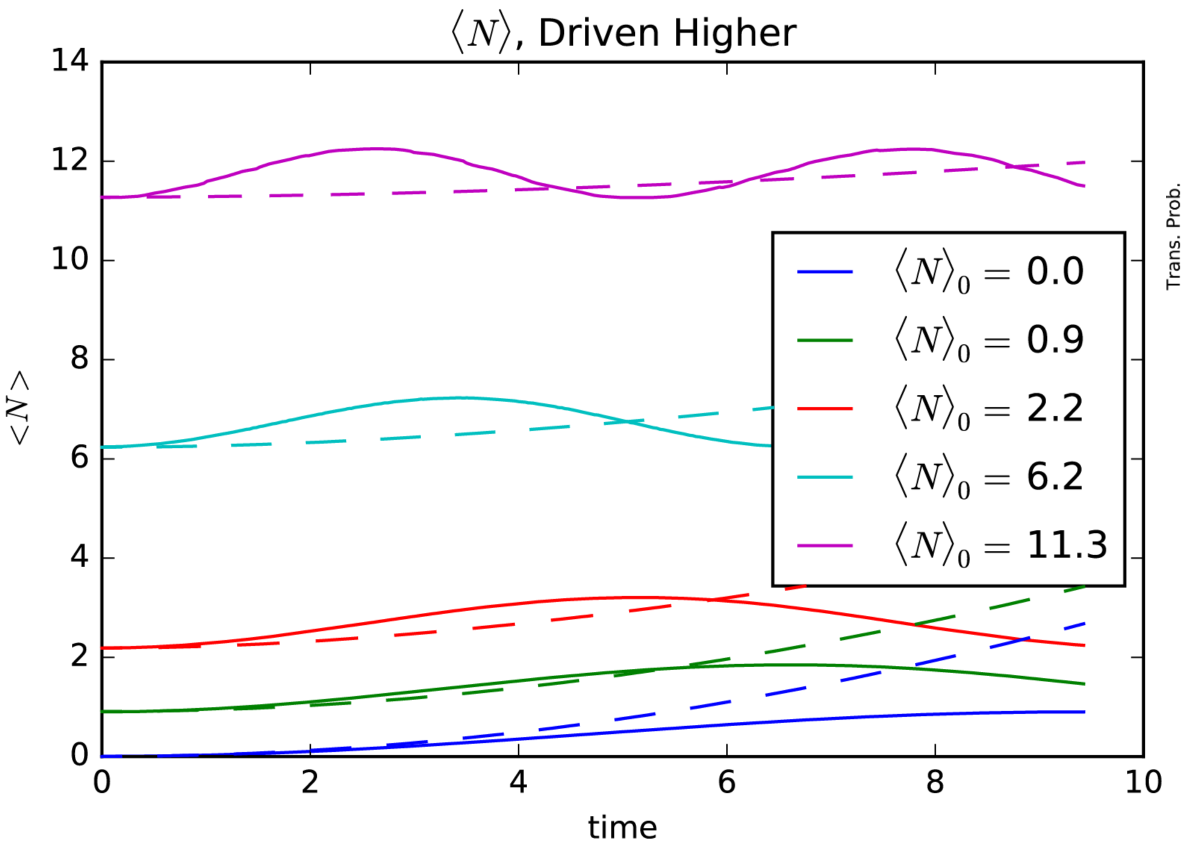


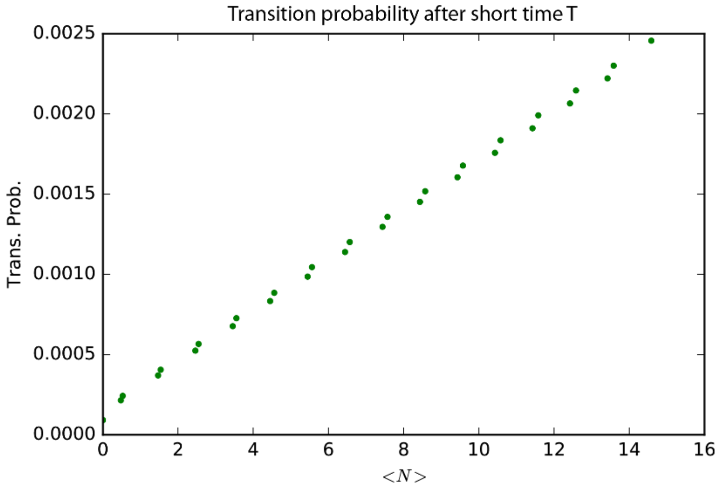
Reinier W. Heeres *et al*, PRL **115**, 137002 (2015)



Coherent axion-photon oscillations

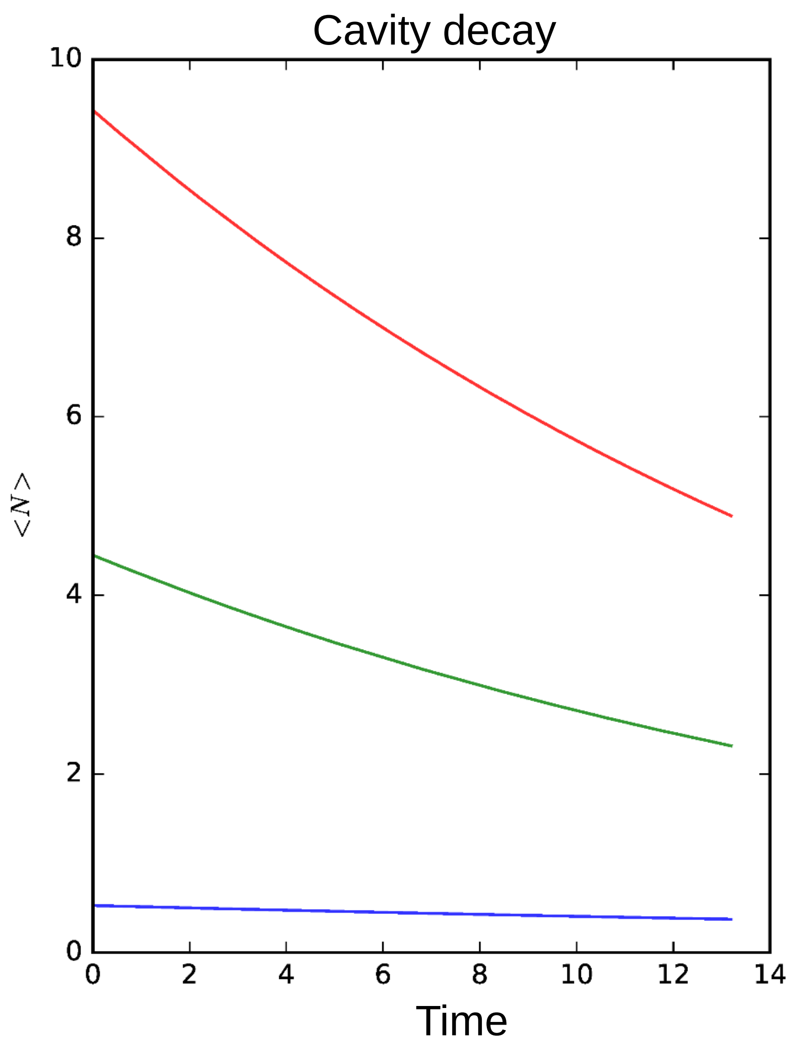
- Now we have a simple two-level system behavior
- The Rabi rate is enhanced in higher Fock states
- Conversion rate at short times increases linearly with *N*.





Effect of cavity decay

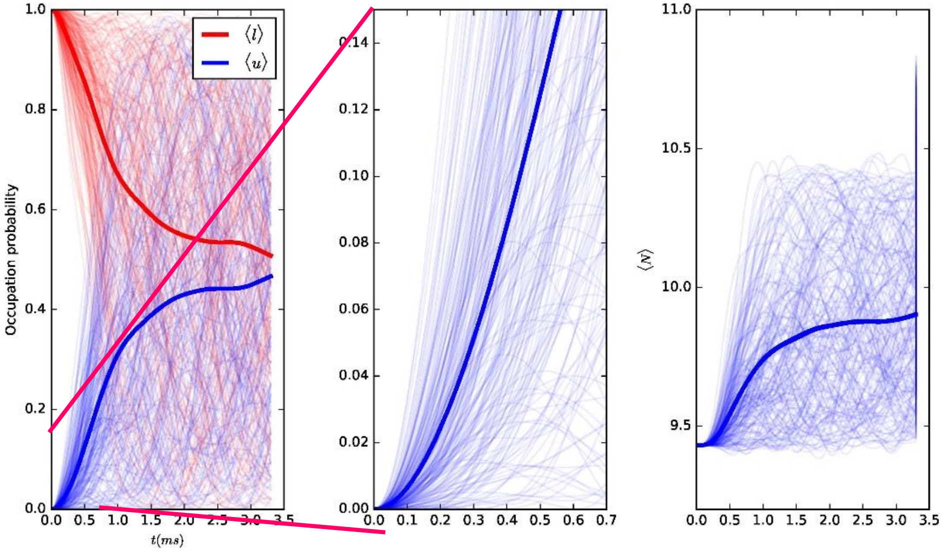
- Decay of higher Fock state is N times faster
- Need $Q_c > NQ_a$
- Assume cavity is prepared in Fock state, wait for axion coherence time, then readout.



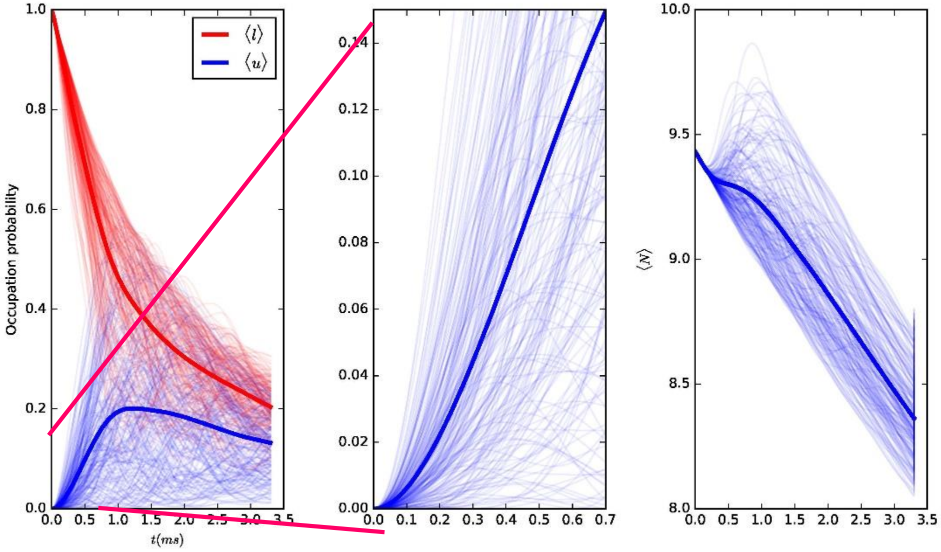
Effect of axion finite width

- For finite axion wave correlation time, the transition probability rises quadratically, then saturates
- Its most efficient to initiate a new trial when it stops growing quadratically.

No cavity decay



Significant cavity decay



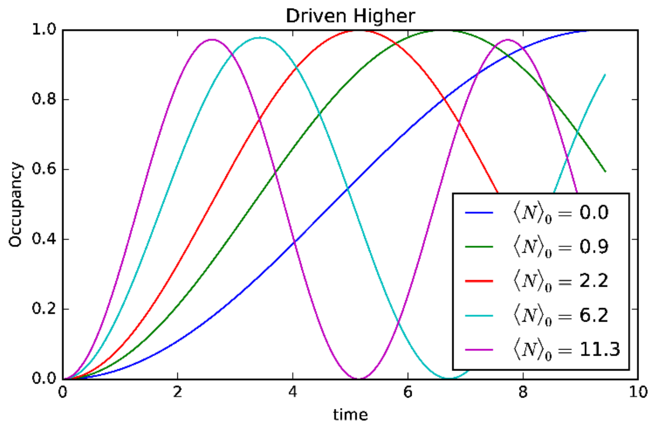
Overall measurement strategy

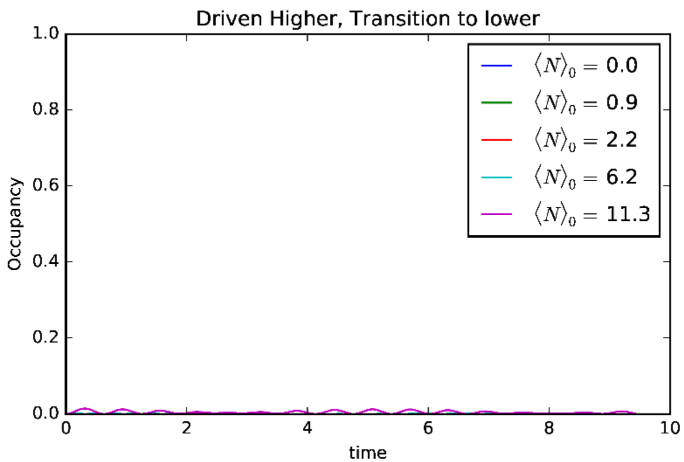
- Initialize cavity in a Fock state
- Wait axion coherence time
- Measure total # photons in cavity
- Repeat n times, where n = $3/P(\tau_a)$ for 3σ
- Overall scan time is reduced by factor N (in regime where signal dominates).
- Can win more if noise dominates

Another approach: Resolve final photon state

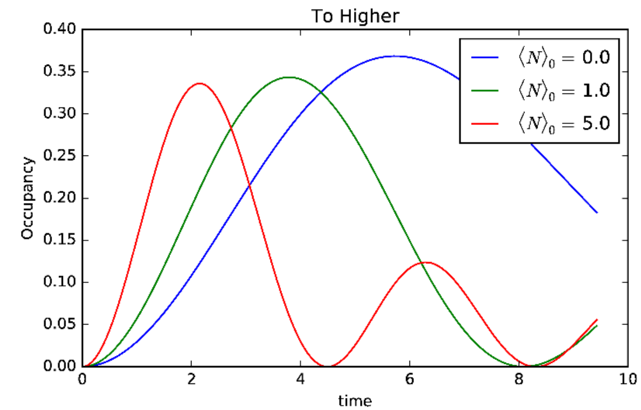
- Look at transitions N→N+1 or N-1
- Even for linear cavity, individual Rabi rates increase for higher initial states. Just need to prepare and measure Fock states.

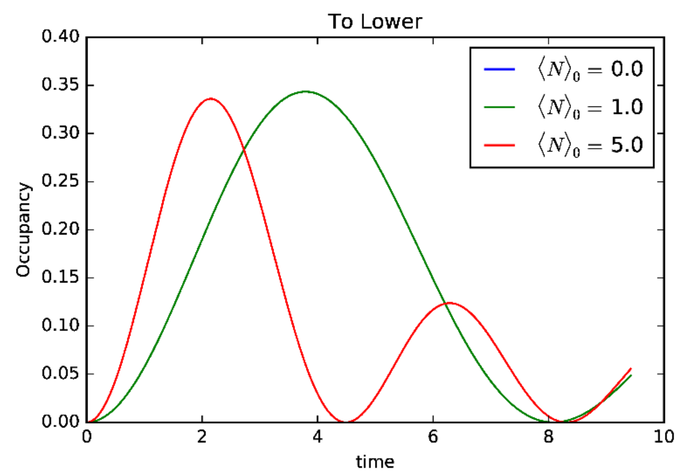
Non-linear cavity





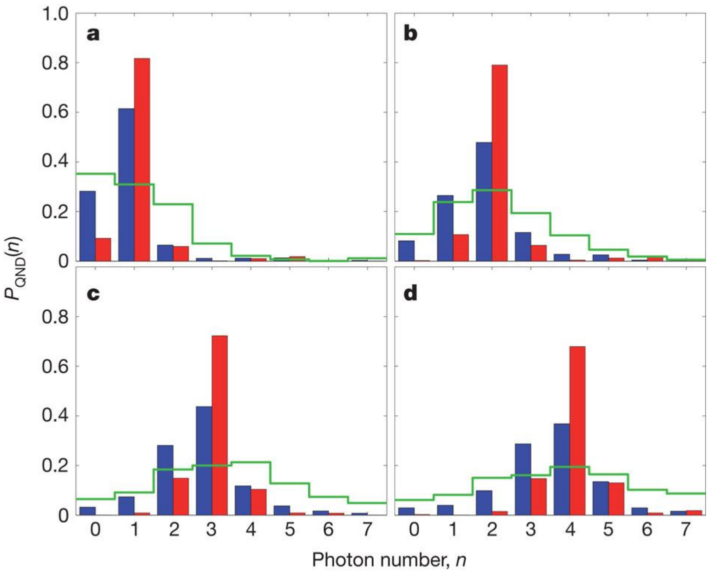
Linear cavity





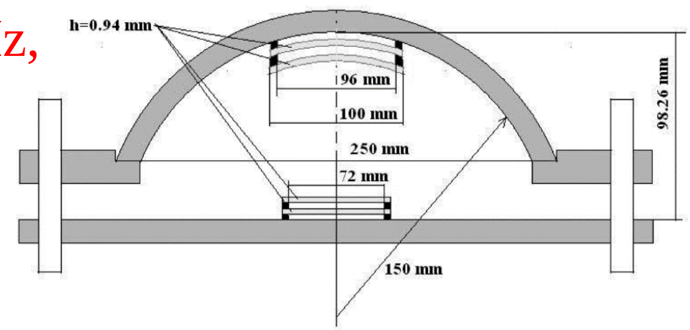
Experimental challenges

- cQED methods with superconducting circuits are rapidly improving.
- Q can be $>10^{10}$ without magnetic field in superconducting cavities
- Hard to get high Q in large magnetic field
- Dielectric cavities are one option

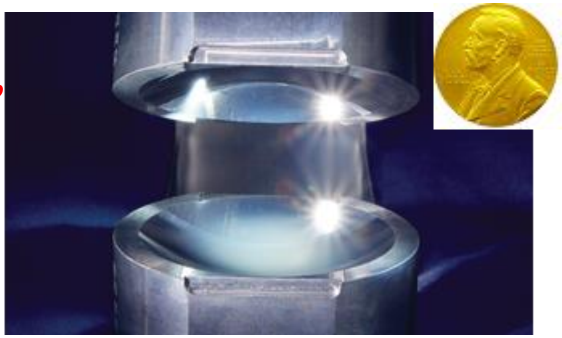


Clément Sayrin *et al*,
Nature **477**, 73 (2011).
Serge Haroche, Nobel Prize 2012

f = 39 GHz,
Q=5 $\times 10^5$



f = 50 GHz,
Q=4 $\times 10^{10}$



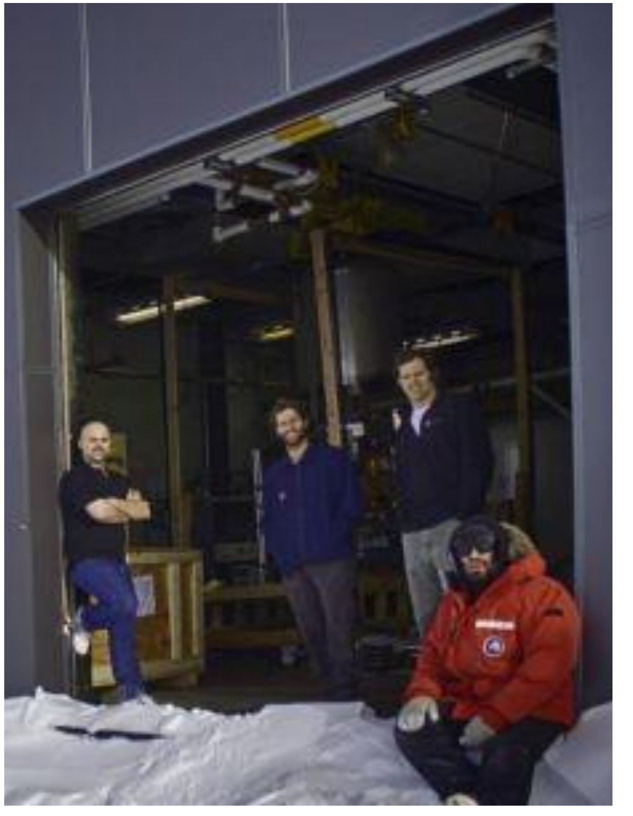
Conclusions

- Atomic co-magnetometers set the most stringent limits on anisotropy in the speed of light
- Search for axion spin-mass force on 20 cm scale is underway, will exceed astrophysical bounds

Junyi Lee

- Possible improvement in sensitivity of cavity axion/hidden photon searches using bosonic enhancement

Morgan Hedges



Marc Smiciklas
Morgan Hedges
Neal Schiebe
Andrew Vernaza

Funding:NSF